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Cite as: AIP Conference Proceedings **2445**, 020013 (2022); https://doi.org/10.1063/5.0085763
Published Online: 12 May 2022

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RAISELIFE Project Extends the Lifetime of Functional CSP Materials

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Abstract. The RAISELIFE project was conducted from April 2016 until March 2020 and was funded within the H2020 program of the European Commission (Grant 686008). The project aimed at developing novel materials with extended lifetime and performance for parabolic-trough and solar tower CSP plants and thereby reducing electricity generation costs. In order to assess the expected durability of the novel materials, improved accelerated aging and qualification methods simulating in-service conditions in different climates were developed. The project brought together a broad consortium formed of industry partners, SMEs and research institutes of the CSP and material science sector. This paper summarizes the main developments and takeaways from the RAISELIFE project.

INTRODUCTION AND METHODOLOGY

The following materials were investigated in RAISELIFE: 1) protective and anti-soiling coatings for glass reflectors, 2) thin-glass composite reflectors for heliostats, 3) high-temperature secondary reflectors, 4) absorber coatings for tubular solar tower receivers, 5) absorber coatings for non-evacuated line-focus collectors, 6) anti-reflective coatings for glass envelope tubes, 7) corrosion resistant high-temperature metals and coatings for molten salt. FIGURE 1a illustrates some of the material developments.

The testing activities involved outdoor exposure, accelerated testing in climate chambers, accelerated testing in concentrated solar flux test beds and in-service testing in the field. Failure modes were examined and the developed materials were optimized in terms of lifetime. Performance and degradation models were derived and a techno-

SolarPACES 2020
AIP Conf. Proc. 2445, 020013-1–020013-9; https://doi.org/10.1063/5.0085763
Published by AIP Publishing. 978-0-7354-4195-8/$30.00

economic analysis was conducted using system simulation tools. This had the aim to determine the economic benefit of the novel developments compared to the state of the art materials (see FIGURE 1b).

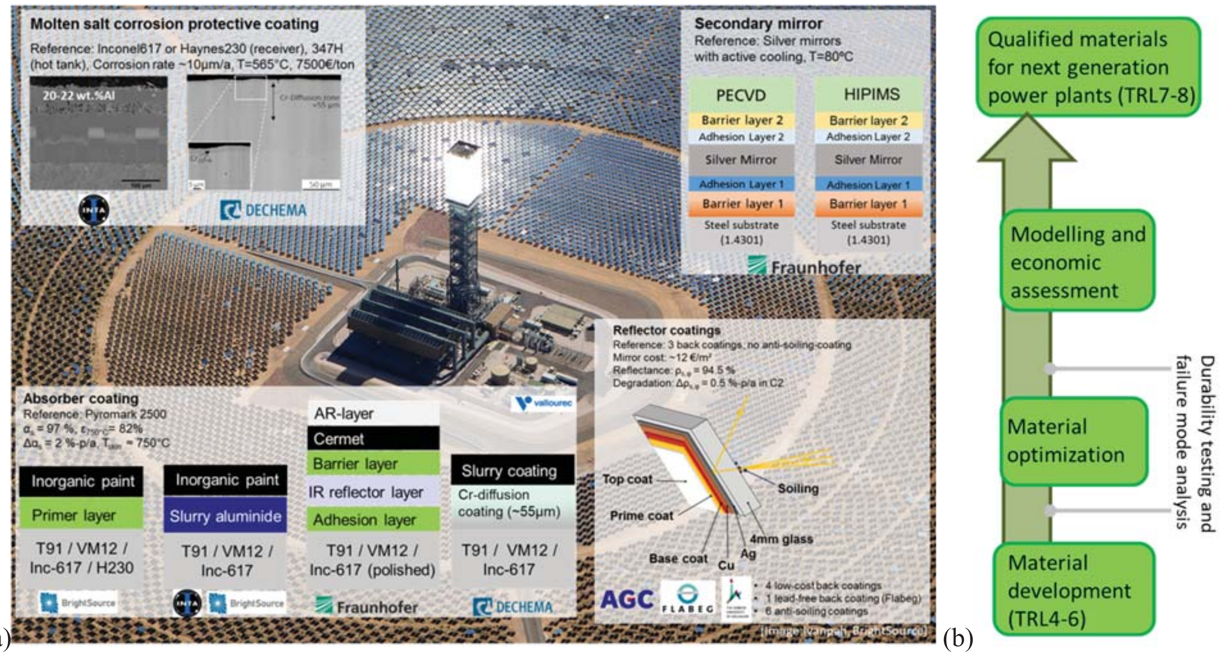
(a)  (b)

FIGURE 1. a) Selected coating and material developments in RAISLIFE and KPI's of state of the art materials. b) RAISELIFE approach to qualify novel functional CSP material developments

RESULTS

Protective and Anti-Soiling Coatings for Glass Reflectors

Corrosion resistance of silvered-glass mirrors is mainly determined by the protective backside coating system. Two commercial and five novel mirror coatings (see TABLE 1) were analyzed within the project in 11 outdoor environments and by accelerated aging. The aggressiveness of the outdoor exposure sites was determined categorizing them into corrosivity (C1-C5 according to ISO9223, being C1 the least corrosive site) and erosivity classes (E1-E3, according to [1, 2] being E1 the least erosive site). Negligible degradation was measured for all mirror types (except RFA5) in low corrosive, desert CSP-site conditions (C2-E1 environment). Under these conditions, usage of 2-paint layered mirror coatings RLA2, RLA3, RLA4, RLB3 is advisable to save CAPEX, leading to an expected LCOE reduction of -0.2%. Higher degradation rates were determined for sites close by the coast (C4-E1). The 3-paint layered commercial coating showed to be the best choice for such kind of environment.

TABLE 1. Mirror coating systems tested in RAISELIFE (the reflectance ρ is expressed in sun-conic solar-weighted specular reflectance at incidence angle of 10° and acceptance angle of 12.5 mrad).* value after 2 years of exposure

Material code	RLA1	RLA2	RLA3	RLA4	RLA5	RLB1	RLB2
Number of layers	3	2	2	2	2	2	2
Characteristics	Commercial	Low-cost	Lead-free	Low-cost	Powder coating	Commercial	Low-cost
Initial ρ	95.1	95.1	95.3	95.4	94.6	95.6	95.6
ρ after 3 years in C2-E1	95.1	95.0	95.3	95.3	Fail	95.6*	95.5*
ρ after 3 years in C4-E1	94.9	94.8	95.0	94.9	Fail	95.4*	95.4*

Accelerated aging methodologies were improved and are currently prepared for transfer to the IEC TC117 standardization group [3, 4]. The developed corrosion prediction method is based on correlating measured corroded area between outdoor corrosivity classes and the accelerated CASS test (ISO 9227). As seen in FIGURE 2a the predicted lifetime of the novel low-cost 2-paint mirror coatings is as high as for the commercial 3-paint coatings in a

C2 environment. For C3 and C4 sites however, the commercial 3-paint coatings proved to perform better. As indicated before, usage of low-cost 2-paint mirror coatings is only advisable for corrosivity sites of C2.

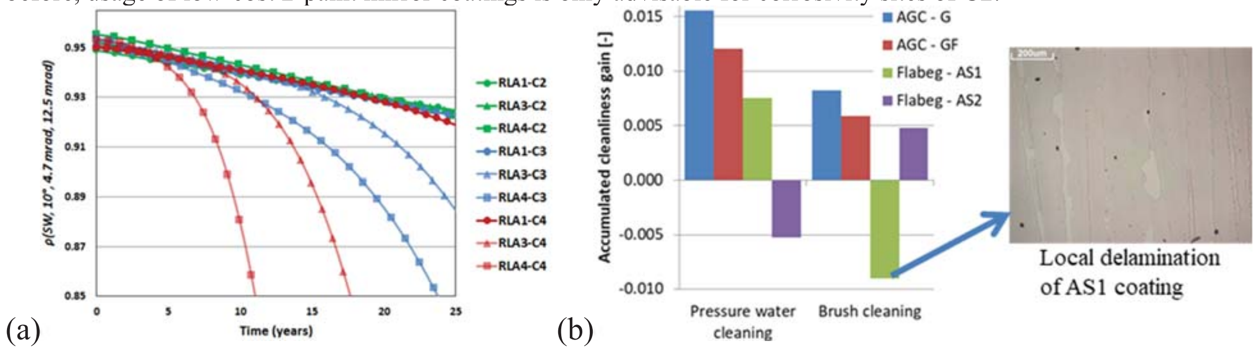


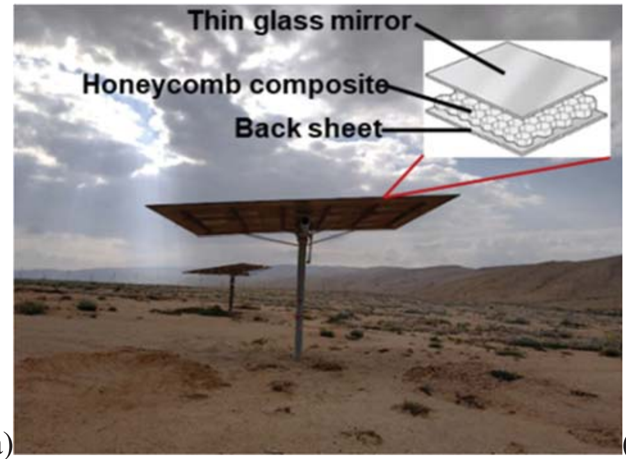
FIGURE 2: (a) Predicted reflectance drop of 3 materials with different protective back coatings during exposure at exposure sites of corrosivity C2, C3, C4 (erosivity in all sites is E1). (b) Accumulated cleanliness gain of different anti-soiling coatings and cleaning techniques after 22 months of exposure at for AS1 & AS2 and 14 months of exposure for G & GF at CIEMAT's Plataforma Solar de Almería.

In addition to protective mirror coatings, 8 novel anti-soiling coatings deposited on the front glass of the reflector were tested. These coatings have the potential to tackle certain issues related to solar field performance: avoid strong soiling, maintain higher reflectance, less frequent and easier cleaning in connection with lower water consumption. Through outdoor and accelerated testing, it was possible to quantify the advantage of the coatings, that is, their cleanliness gain compared to uncoated reference mirrors. Depending on the type of coating and the cleaning technique applied, a cleanliness gain of over 1.5%-p was determined (see FIGURE 2b). Mechanical damages due to abrasion were identified as the main degradation mechanism for the coatings during the outdoor exposure tests (see degradation due to cleaning on coating AS1) [5]. FIGURE 2b does not show the tested experimental liquid coating, which was discarded due to strong degradation, and three coating developments from HUJI, which showed promising lab performance but long-term outdoor data, is lacking at the current stage of development.

Thin-Glass Composite Reflectors for Heliostats

A novel composite heliostat was designed and installed by BightSource (BSII) at a pilot site in Israel in autumn 2018 (see FIGURE 3a). Due to the high stiffness and low weight of the composite sandwich material, the size of the heliostat was increased from traditional BSII design of 25.7 m² to 40 m², maintaining its resistance to wind loads >45 m/s. The increased size has a great economic impact on all works related to the solar field, such as dirt moving, foundations, roads, etc. The entire heliostat was assembled in one single afternoon and using very simple tools. The utilization of the composite sandwich also allowed the selection of (ultra-) thin glass mirrors instead of conventional self-sustaining 4 mm glass reflectors, obtaining about 0.5%-p higher reflectance due to reduced absorptance losses in the glass. Four types of thin glass mirrors (of 1 mm thickness), with reduced back side coating systems, and one experimental ultra-thin glass (0.2 mm) mirror were glued to the composite material and tested as candidate reflective surface for the heliostat. The ultra-thin mirror was discarded in an early project stage, mainly because of high manufacturing costs and low mechanical protection (e.g. by small impacts). All sandwich reflectors showed superior resistance to corrosion compared to traditional reflector materials because the backing composite material acts as an excellent diffusion barrier protecting the reflective silver layer.

Laser scanning of the prototype composite heliostat has been performed at the BSII pilot site, as well as in laboratory tests on small 50 x 50 cm^2 samples by Fraunhofer. Both, at laboratory tests as well as on the large heliostat, it was recognized that: (1) the impact of environmental temperature on the composite material creates an optical deformation (unlike the negligent impact for 4 mm glass mirror); (2) The large surface of the thin-glass composite panels and the supporting structure suffer deformations due to the gravitational force at the various angular positions of the heliostat (see FIGURE 3b). Altogether, the impact on the overall optical efficiency loss can be in the order of ~1 %, with potential to be minimized in future designs. Nevertheless, the decrease in performance is largely outweighed by the potential cost reduction in the order of 30%, mainly due to the allowable larger reflective surface. The thin-glass composite heliostat is an attractive improvement – surpassing the original US DOE road map goal for solar field reflectors from \$75/m^2 to about \$50/m^2 heliostat cost.



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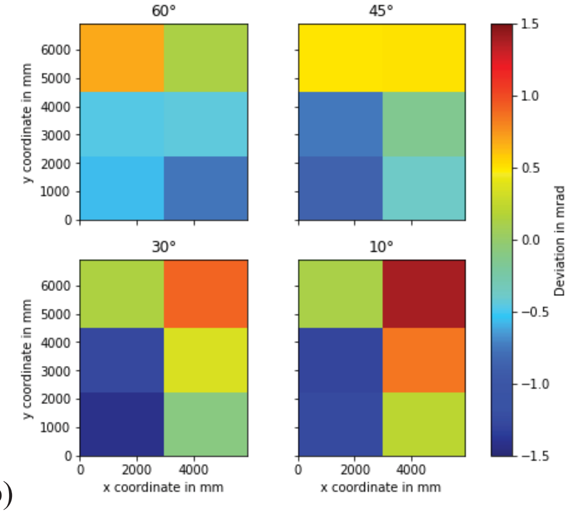

(b)

FIGURE 3. (a) Heliostat of size 6.9 x 5.9 m² erected in Israel, including sandwich reflector (composite + thin glass mirror), (b) Slope deviation of heliostat facets due to gravitational loads for elevations angles 10, 20, 45 and 60°.

High-Temperature Secondary Reflectors

Fraunhofer investigated a secondary reflector based on highly polished steel substrates and a silver-based sputtered thin film coating [6] with the aim to be employed in a solar tower without a cooling system and reducing its LCEO up to 1.9%. Modelling of a reference solar tower plant showed that the backside of the reflector must be black (emissivity: 0.95) to dissipate the heat and the reflectance should >0.95 to assure that the material temperature limit of 400°C is not exceeded. The second generation of the Fraunhofer mirror reached 95.5% reflectance but stability under concentrated flux and in the conducted environmental climate chamber tests still needs to be improved. FIGURE 4 shows the evolution of hemispherical solar reflectance $\rho_{s,h}$ in the solar furnace test (10 days of operation at 350 kW/m^2, which involved 36 h at 400°C and around 20 temperature cycles from 50°C to 400°C) [7].

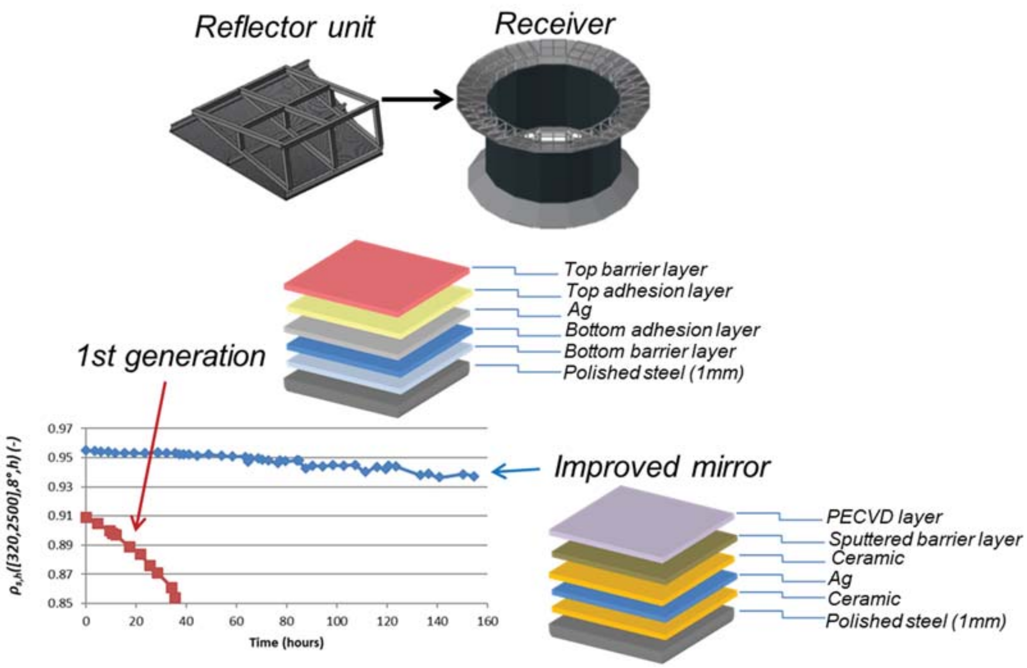

FIGURE 4. Secondary reflector design, material composition of 1st and improved generation as well as performance in solar furnace aging test conducted at CIEMAT's Plataforma Solar de Almería (PSA).

Absorber Coatings for Tubular Solar Tower Receivers

Four novel absorber coatings for solar towers have been developed within the RAISELIFE project: a ceramic paint (BSII), an aluminide primer (INTA), a PVD selective coating (Fraunhofer) and a multi-metallic diffusion coating (DFI). The coatings were tested under a large set of accelerated aging tests [8, 9]. Based on the detected degradation, the formulation of each coating was improved and a second generation was developed. One example of the conducted optimization is the combination of the selective coating with the aluminide primer with the aim to suppress diffusion of coating elements into the substrate (coating E INTA+Fraunhofer). FIGURE 5 shows the initial optical properties and the degradation rate measured for the second generation of coatings as applied on Inconel 617 substrate under accelerated aging compared to the reference coating Pyromark2500 (in addition the BSII coating applied on Haynes230 substrate is shown for comparison). It can be seen that the BSII coating achieves similar optical performance than Pyromark2500 while the measured degradation is considerably lower. The developed lifetime model predicts that the solar absorptance of the BSII coating will remain above 95% for about 7 years on T91 and about 15 years on Inconel 617. As a result of the testing activities carried out in the project, BSII decided to employ the novel absorber coating in the commercial solar tower plant in Dubai. The LCOE reduction resulting from this new coating is expected to be -1.1% compared to a reference plant using Pyromark2500, mainly due to longer recoating intervals and less down-time of the plant [10].

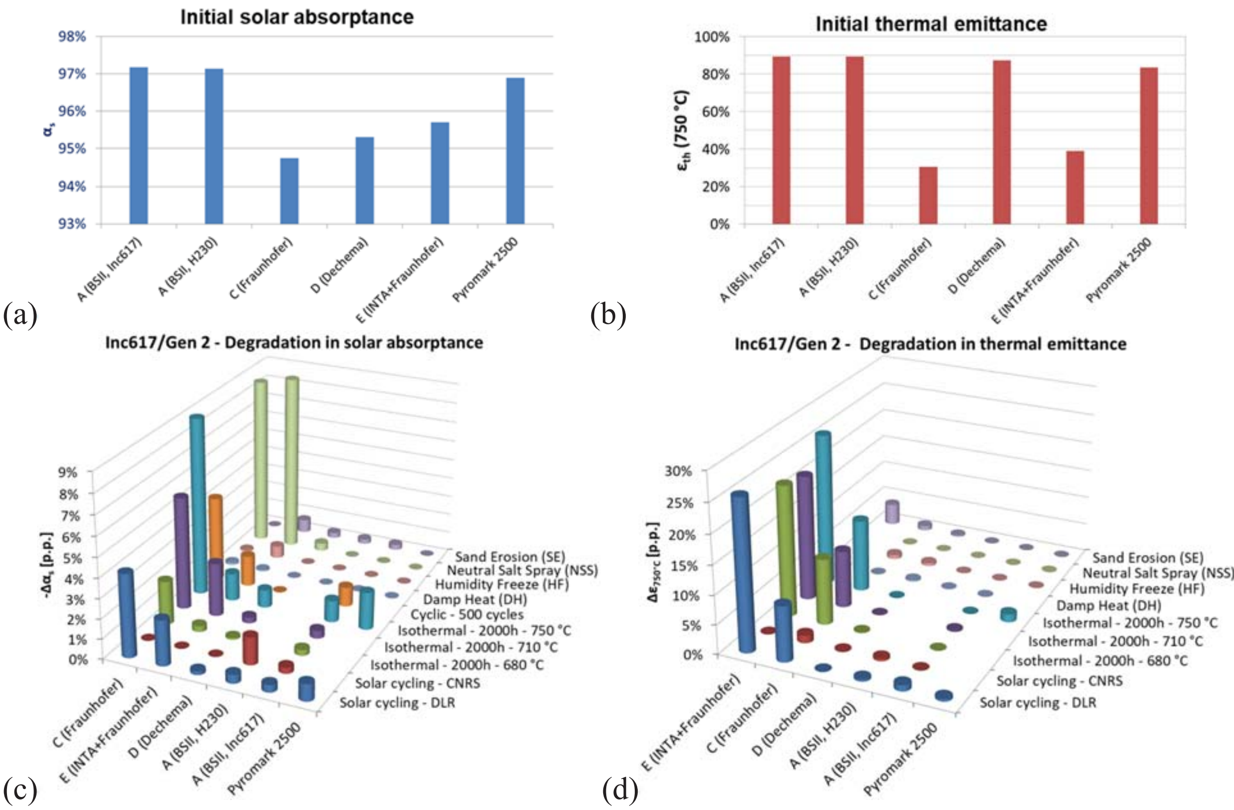

FIGURE 5. Left: initial (a) and measured decrease (c) in solar absorptance of the different coatings on Inconel 617 substrate after the accelerated aging tests applied. Right: initial (b) and increase (d) in thermal emittance (750°C) after accelerated aging. The values of the reference state of the art coating Pyromark2500 are based on own measurements and literature data.

The previous absorber coating generation employed by BSII in Ivanpah already showed good results: after 7 years of operation (+ 2 years construction) no major failures occurred; only local repair works were conducted and rarely entire panels were recoated (see FIGURE 6a). On-tower recoating is desirable to reduce the O&M cost but also challenging: cleaning and surface preparation, painting, and the complicated solar curing profile needs to be conducted at tower heights of more than 200 meters. In RAISELIFE it was demonstrated for the first time, that solar curing is possible proving similar optical parameters and durability of solar and furnace cured coatings in solar dish cycling tests at CNRS and PSA (see FIGURE 6b). To enhance coating lifetime further, BSII developed an automatic coating machine able to coat prototype panels up to 2x2 m² (see FIGURE 6c). Coating thickness tolerances of only 5 µm were achieved (compared to 20 µm for manual painting), thus reducing coating "weak points".

FIGURE 6. (a) Recoating of receiver panel in Ivanpah power plant by BSII, USA, (b) Testing of solar cured absorber samples at CIEMAT's PSA, (c) Mid-sized automatic coating machine while coating a test panel.

Absorber Coatings for Non-Evacuated Line-Locus Collectors

Selective absorber coatings developed by CIEMAT have been improved during the RAISELIFE project, adding an additional chromium infrared reflective layer to reduce thermal emittance. Solar absorptance reached 0.955 and thermal emittance has been reduced from 0.133 to 0.087 for absorber coatings prepared directly on a stainless steel substrate. Thermal durability has been tested at different temperatures and the absorber has maintained optical properties at 400°C in air during 15 months of furnace testing. Only negligible degradation has been detected after 14 months of field testing in a parabolic trough collector heated up to 180°C by Soltigua. First signs of degradation are seen at 450°C (see Table 2).

TABLE 2. Optical properties of chromium coated stainless steel selective absorber as prepared, after 15 months at 400ºC and after 12 months at 450°C.

	Initial	**After 15 months at 400°C**	**After 12 months at 450°C**
Solar absorptance α	0.954	0.956	0.932
Thermal emittance ε(250°C)	0.087	0.091	0.137

Abrasion Resistant Anti-Reflective Coatings for Glass Envelope Tubes

The anti-reflective coating developed by CIEMAT has been improved during the RAISELIFE project: 1) the solar transmittance has been increased from 0.965 to 0.972, 2) the mechanical resistance according to the TABER abrasion test has been improved so that the number of strokes required to remove the coating completely has been increased from 40 to 100.

The improved coating formulation has been deposited on full-scale receiver tubes in the commercial manufacturing line of Archimede Solar Energy in Italy. Afterwards, the produced samples were tested in a linear Fresnel collector operated by Soltigua up to 180°C. The transmittance stayed between τ =95.1% - 96.1% after 12 months of field testing, including 2 cleaning cycles per month.

Corrosion Resistant High-Temperature Metals and Coatings for Molten Salt

With the aim to develop cost effective materials for molten salt environments, corrosion resistant coatings for ferritic steels and novel corrosion detection sensors [11] have been developed. Vallourec provided material as flat coupons (20x10x3 mm³) of T91 and VM12 to be coated and used for the lab tests. T91 and VM12 are respectively 9% and 11% chromium steels currently used in conventional boilers at around 560°C to 600°C. Molten salt immersion tests were performed with at least three test pieces of each material with exposure times up to 10,000 hours.

INTA developed three aluminide coatings named INTA 1-3 [12, 15, 16]. Because INTA3 showed the highest mass gains after 1,000 h at 560°C and 580°C and INTA2 evidenced interdiffusion between coating and substrate, INTA1 (see FIGURE 1a top left) was selected as the best coating to continue for the long-exposure tests. DECHEMA developed two diffusion coatings both of them were deposited via the industrially well-established powder pack cementation method [13]. The first coating (DFI1) was manufactured by the co-deposition of Cr and Mn, which resulted in the formation of Cr-Mn carbide at the surface as well as a Mn-diffusion zone. However, DFI1 coating formed non-protective fast-growing oxides as well as significant outward diffusion of Fe and consequentially a high mass loss was observed during short term exposure at 560°C. Hence a second coating (DFI2) was manufactured by the sole deposition of Cr and resulted in the formation of a homogenous $Cr_{23}C_6$ layer (see FIGURE 1a top left). This coating showed a higher corrosion resistance in molten salt exposure tests compared to DFI1 and thus was selected for the long-exposure tests and the subsequent microstructural characterization.

The results of the static long-term tests are shown in FIGURE 7, where also the performance of nickel base alloys Inconel617 and Haynes 230 was included for comparison. The results show excellent performance of the coatings with negligible mass changes compared to non-coated substrates even after 10,000h of testing at 580°C in solar salt. The coated steels also showed much better behavior under cyclic (300-580°C in solar salt) and under dynamic conditions (salt flow rate of 0.2 m/s at 580°C). From a corrosion point of view, the INTA1 coating was very stable, maintaining its morphology and composition whatever the test conditions. Only a very thin oxide scale was observed after long term exposure. The DFI2 coating developed a slightly thicker oxide and evidenced local attacks. Slow strain rate tests (SSRT) carried out by Fraunhofer at 580°C in air and in salt indicate that the mechanical properties changed during the coating process [14]. An important outcome of the tests is that no stress corrosion cracking could be observed for VM12 and T91, which would result in fracture without significant plastic deformation.

Different corrosion tests were performed under cyclic, static and dynamic conditions up to 1,000 hours in order to assess the effects of molten salts on the Heat Affected Zone (HAZ) of weld joints. The best coatings from the previous corrosion test were selected: T91-IN617; DFI2- (T91-IN617) and INTA1- (T91-IN617). Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, was used for the manufacturing of the weld joints between T91 and IN617. The manufacturing of the weld bevels was carried out at Vallourec Research Center Germany. Finally, the entire weld joint was subjected to a post weld heat treatment in a furnace. An example of the samples prepared are shown in FIGURE 7b. This Figure also shows the normalized weight change versus time in static conditions. It can be seen that regardless of the type of the coating, coated weld joint samples showed a very stable behavior up to 1000 h, whereas the uncoated weld joint exhibited fluctuations in the weight change diagram. Cr-diffusion coated T91/IN-617 samples showed a slight mass loss in the early stages of the exposure which is associated with the dissolution of the pristine $Cr_{23}C_6$ layer. INTA-aluminized samples showed a negligible weight change which can be interpreted as a highly protective behavior.

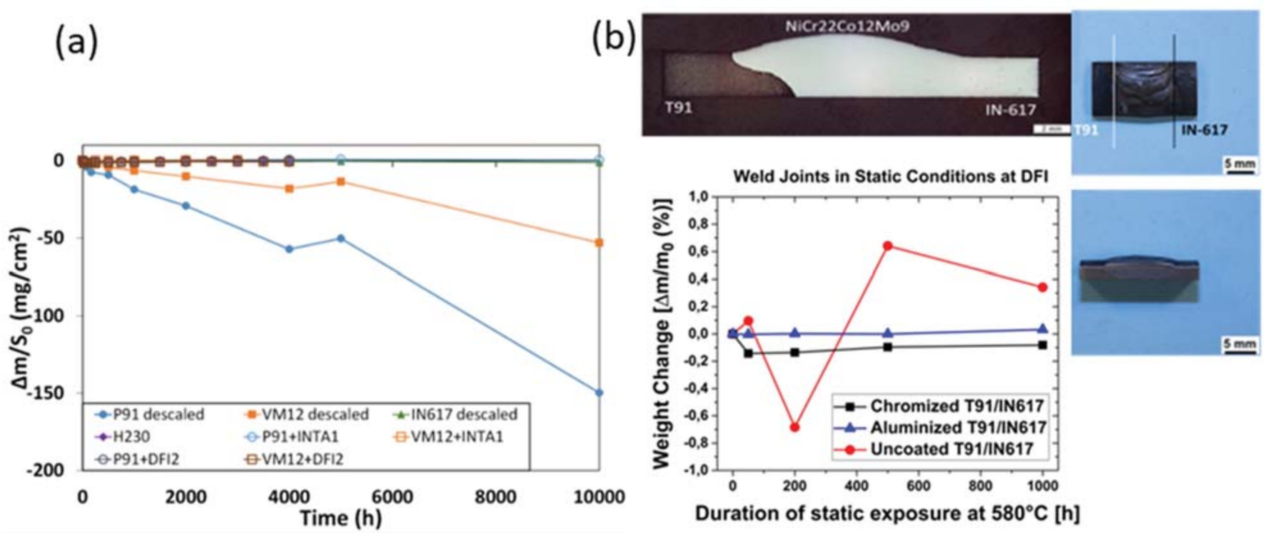

FIGURE 7. (a) Gravimetric comparison between coated P91 and VM12 by INTA and DECHEMA versus uncoated substrates and nickel base alloys in contact with solar salt at 580°C under static conditions up to 10,000 h. (b) Testing of coated and non-coated T91-Inc617 weld joints up to 1,000h in solar salt.

SUMMARY AND CONCLUSIONS

Among the highlights of the achievements of the RAISELIFE project the following points can be remarked:

- Qualification of a novel receiver coating developed by BSII, employed in the commercial 100MW$_e$ DEWA solar tower project in Dubai. The lifetime model predicts that the solar absorptance of the coating will remain

above 95% for about 7 years on ferritic steel substrate T91 (for steam receivers) and about 15 years on nickel base alloy Inconel 617 (for molten salt receiver). The higher lifetime compared to the state of the art Pyromark coating leads to an expected LCEO reduction of about -1.1%.
- Validation of durability of solar cured receiver coatings, opening the possibility to cure the coating directly on the top of the tower. This reduces expensive panel dismantling and furnace curing, fossil fuels (gas burners) as well as down-time of the power plant.
- An automatic coating machine prototype has been built which achieves 4 times lower thickness variation than manual painting and thus reduces possible hot spots of the coating during operation.
- Low-cost 2-layer protective coatings for reflectors showed to be as durable as 3-layer systems at exposure sites of low corrosivity (C2), with degradation rates of 2%-p in solar reflectance after 20 years according to the developed lifetime model. In C3 environments, the degradation is slightly higher compared to 3-layer systems (4%-p vs. 2%-p).
- Design and construction of a composite thin glass heliostat for wind loads >45 m/s at low weight and possible cost reductions of 30%, lowering expected heliostat cost from 68 €/m² to about 45 €/m².
- Anti-soiling coatings for the front glass of mirrors have shown to be able to increase the reflector cleanliness up to 1.5%-p.
- Development of a selective receiver coating for non-evacuated line focusing receiver tubes operating up to 400°C. Negligible degradation after 18 months of in-service testing and >15 months of furnace testing.
- Improvement of the abrasion resistance by factor 2.5 of an anti-reflective coating for evacuated line focusing receiver tubes. The coating was deposited in an industrial coating line on a commercial receiver tube and was validated during 12 months of in-service testing in a linear Fresnel collector.
- Development of weldable, cost-effective protective coatings for ferritic steels in molten salt environment. Stability proven for 10,000 h during static and dynamic tests at 580°C in solar salt.
- Improvement of the durability of a novel high-temperature secondary reflector, albeit stability at 400°C has not been fully demonstrated. The secondary reflector has potential to increase the electricity yield by 1.57%, given that it will withstand the heat load.
- Publication of a catalogue of best practices, an exploitation brochure and the 40 presentations given at the two RAISELIFE dissemination workshops are available on the project website.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 innovation programme under grant agreement Nr. 686008, project RAISELIFE. We acknowledge all contributors who collaborated on the project that could not be listed as authors, as well as former consortium partners Flabeg and Corning.

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